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13. ABSTRACT (Maximum 200 words)

This work achieved several substantial results. A highly stabilized laser system suitable for many detailed studies of data storage phenomena was constructed and made to work. This laser was essential for the investigations which followed. Using the stabilized laser, a real time correlator was demonstrated, which correctly identified all occurances of a test sequence imbedded in random data. This correlator is the first demonstration of the use of phase modulation to store and retreive data in time domain hole-burning. In the frequency domain, narrow holes were burned and scanned, and information storage at a spectral density exceeding 50,000 bits per spot was demonstrated, with perfect recall and excellent signal to noise. We have also made the first demonstration of a novel technique for storing and retreiving phase modulated data streams with time domain spectral hole-burning. This demonstration has been disclosed for patent purposes.

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AFOSR-TR- 94 0312

TECHNICAL REPORT
AFOSR CONTRACT #F49620-92-C-0066

May 2,1994

Michael Jefferson

IBM Almaden Research Center
650 Harry Road
San Jose, California, 95120-6099

PREFACE

This report describes work performed under AFOSR contract #F49620-92-C-0066. This work was done at the IBM Almaden Research Center, in San Jose, California between October 1, 1992 and December 31, 1993. The principal investigator was Michael Jefferson.

The focus of the work was the investigation of time-domain spectral hole-burning phenomena, particularly as related to information storage and processing applications. The particular interest area of the investigation was of the role of optical phase effects on the storage and retreival of information in rare earth doped crystaline materials. The material studied was $Eu^{3+}{:}Y_2SiO_5$.This material has the highest known ratio of inhomogeneous to homogeneous linewidths, and has the theoretical potential to store as many as perhaps 10 million data bits in a single optical spot.

This work achieved several substantial results. A highly stabilized laser system suitable for many detailed studies of data storage phenomena was constructed and made to work. This laser was essential for the investigations which followed. Using the stabilized laser, a real time *correlator* was demonstrated, which correctly identified all occurances of a test sequence imbedded in random data. This correlator is the first demonstration of the use of phase modulation to store and retreive data in time domain hole-burning. In the frequency domain, narrow holes were burned and scanned, and information storage at a spectral density exceeding 50,000 bits per spot was demonstrated, with perfect recall and excellent signal to noise. We have also made the first demonstration of a novel technique for storing and retreiving phase modulated data streams with time domain spectral hole-burning. This demonstration has been disclosed for patent purposes.

TECHNICAL DISCUSSION: STABILIZED LASER

The rare earth doped crystaline materials currently being studied by investigators into time domain hole-burning phenomena are characterized by extremely narrow homogeneous linewidths at low temperatures. The linewidths range from tens of kilohertz to only 200 Hz in materials like $Eu^{3+}:Y_2SiO_5$. In order to investigate the physics and technology capable of utilizing this narrow linewidth, it is highly desireable to use a laser which has a linewidth comparable to or narrower than that of the material. In particular, it is impossible to study phase modulated techniques if the laser is not phase coherent over the required time scales. For this reason, a substantial amount of effort and resources were invested in the development of a laser which was suitable for making these investigations.

The laser source for these experiments was a Coherent 699 ring dye laser using Rhodamine 6G dye. This laser has a linewidth of several Mhz, and a frequency drift of 100 MHz per hour(or worse). In order to provide a better linewidth, a Hall/Hansch external laser stabilizer was constructed. This stabilizer utilizes a high finesse reference cavity to monitor the phase/frequency fluctuations of the laser, and applies phase/frequency corrections to the laser beam by means of acousto and electro-optic modulators external to the laser cavity. Control elements inside the laser cavity are also utilized to control the long term drift of the laser. Using these techniques, a laser linewidth estimated at 1 kHz relative to the reference cavity was achieved. This linewidth was estimated from measurements of the residual error signals in the control loop and the known transfer function of the reference cavity. Measurements of frequency domain spectral holes showed that the achievable hole-widths were much larger than 1 kHz, however. Studies revealed that the reference cavity length was being modulated by mechanical vibrations in the experimental apparatus. Huge amounts of effort were expended addressing this issue. After substantial effort to find and eliminate vibrations, and the construction and testing of other reference cavities, it was decided to employ an additional absolute frequency reference, namely an iodine absorption spectrometer, to control the cavity length.

After procuring a high quality iodine cell with Brewster windows, a saturated absorption iodine spectrometer was built and the cavity length was locked to an iodine hyperfine line with a servo system and a piezoelectric actuator (PZT) on the reference cavity mirrors. It was fortunate that there were iodine absorption lines within both of the absorption lines of the sample of $Eu^{3+}:Y_2SiO_5$ which was the object of our studies. These absorption lines were strong enough to provide adequate signal to noise ratios to lock the cavity length to within a few kiloHertz, short term, and much below a kilohertz long term.

Frequency domain holes burned with the laser were still wider than desired, with 35 kHz fullwidth half-maximum for the deconvolved laser linewidth being the best result achieved. Nonlinear fits to the scanned spectral hole profiles were highly Gaussian. From this, and from an analysis of the servo system and iodine stabilizer, we concluded that the source of the laser line broadening is a wide deviation, low frequency pertubation. There are several potential sources for this broadening, such as Barkhausen-like domain noise in the PZT structure, Doppler shift of the light due to vibrations of the sample and/or optical elements (mirrors,etc.), or a broadening mechanism such as vibration induced Stark effects or lattice strains occurring over time periods longer than a few milliseconds, but shorter than the measurement times (typically a few seconds). The source of this broadening remains under investigation.

Although the achieved linewidth was less than desired, the laser stabilizer exhibited drifts of less than 200 Hz over periods of 10 seconds or more. Long term drift was very low, since the laser was locked to a highly stable atomic absorption line. This meant that spectral hole patterns burned either in the time or frequency domain were easily accessed at any time during an experimental run, simply by locking the laser to the appropriate hyperfine transition. Since the laser frequency was shifted by a series of acousto-optic modulators, exact and repeatable offsets of the laser frequency by amounts up to 200 MHz in arbitrary steps as fine as 1 Hz could be achieved. It was possible to keep the laser stabily centered over a spectral hole for hours if needed. This capability is unique in the hole-burning experimental community to our knowledge. This combination of high stability of center wavelength and narrow linewidth allowed several significant demonstrations of technological potential to be realized.

FREQUENCY DOMAIN HOLE-BURNING RESULTS

As a test of the laser stability and linewidth, we burned single and multiple spectral holes. A detailed description of these results, which will be presented at the International Spectral Hole-burning Conference at the University of Tokyo, in August, 1994 is attached. These tests allowed us to demonstrate the storage of actual digital data at a spectral density of greater than 50,000 bits per optical spot. Due to the need to keep the laser fluence low, the beam was unfocused, so the volumetric storage density was not significant. The unfocused beam was only a technical detail, and does not preclude the use of tightly focused beams capable of achieving very significant net volumetric densities.

The readout of the data took several seconds. This was determined by the update rate of the frequency synthesizer used to offset the laser frequency, and by the need for a sufficiently low bandwidth to suppress the shot noise in the intensity measurement. The slow readout is an inherent drawback to frequency domain storage in the narrow linewidth materials, as has been known for a long time. Because the spectral holes are narrow, the frequency of the laser cannot be swept at a high rate when measuring them (reading out the data) without seriously degrading the resolution. This is analogous to the sweep rate problem on a spectrum analyser when observing narrow spectral features. The narrower the holes (and thus the higher the spectral density), the slower the access must be in the frequency domain. This restriction does not hold if only a single spectral channel is utilized, as would be the case if holograms were being stored. In that case, the data rate could be very high, conceivably in the gigaHertz range, because the slow spectral access would be offset by the massively parallel spatial readout. This is the best interpretation to put upon the frequency domain data presented here. Using both absorption sites in the sample, and assuming a hologram of 4 mm diameter with 1000 x 1000 pixels (comparable to photorefractive material performance targets), a volumetric density of approximately 4×10^{11} *bits*/cm^3 at the surface of the crystal would be achieved. Current state-of-the-art density for magnetic or optical disk storage is a few gigabits per square centimeter. Thus, a potential storage density increase of more than 100 over the best conventional storage technologies could be achieved in a a material such as Eu^{3+}:Y_2SiO_5 using the spectral density demonstrated in this work.

Assuming a 120 kHz spacing between holograms, access could be achieved in less than 50 microseconds, and if the signal to noise ratio were sufficient that readout could be achieved with a good error rate in 1 millisecond, then the bit data rate would be 1 gigaHertz. This is more than a factor of 10 better than that achieved to date with the best magnetic or optical disk drives. The access time of 50 microseconds to any of 50,000 holograms is a factor of 100 better than that of any DASD (Direct Access Storage Device, e.g. a disk drive).

It would be misleading to assume that this kind of performance could be achieved without overcoming many difficulties. The technical and economic hurdles to be surmounted to make persistent spectral hole-burning storage devices a reality are formidible. With the exception of photo-refractive holographic storage devices, however, there are literally no contenders for the next great storage technology. The minimum requirements of enormous density, very fast access, and ultrahigh data rates disqualify essentially all contending techniques almost immediatly. The need for such a technology is here today and growing quickly. By the end of the century, in the author's opinion, the mismatch between processor capability and storage device performance will be at a critical impasse. Thus it seems essential that research such as that described here must continue to be funded aggressively.

PHASE MODULATED TIME-DOMAIN DATA STORAGE

A major interest area of this research was the exploration of the possibilities of using phase modulation to store information in the time domain, rather than the conventional amplitude modulation. Amplitude modulated photon echos present severe technical challenges if they are to be decoded with a very low error rate. In addition, the fact that only one symbol (either a "1" or a "0") can be represented by signal power, while the absence of signal power (but not the absence of noise) represents the other symbol causes a substantial decrease in the amount of information about the sequence of symbols available to the receiver/decoder. An additional difficulty which amplitude modulated photon echoes present is that the shapes of the echo pulses are not conducive to high densities, since they have intersymbol interference and are difficult to discriminate temporally with tight clocking margins.

Many of these objections could be minimized if it were possible to detect the data stream as modulation of the phase of a continuous echo pulse. A patent on this concept has been granted to the author. It has been believed, and our current work has demonstrated, that information stored by means of a phase modulated data pulse could be recalled with good fidelity. The real time correlator, to be described later, utilizes phase modulation of the data as an essential aspect of its operation. The main technical hurdle to studying the value of the phase modulation technique has been the difficulty in decoding the phase modulations of the echo pulse. Although the data rate for the phase modulation is at a tractable level (tens of Mhz, typically), the phase being modulated is that of the laser beam optical frequency, which is approximately $5x10^{14}Hz$. This frequency is far too high for conventional RF circuits to handle, so some form of local oscillator must be provided to beat the phase modulated carrier to a lower frequency. One of the reasons for building the stable laser was to allow such a local oscillator to be generated. The practical difficulties of actually using the laser as such signal source forced us to rethink the problem, and a simple and elegant solution to the local oscillator problem was found. This solution has been written up and disclosed for the purpose of patenting it.

The essence of the technique is to store not one, but two population gratings in the frequency domain, separated by a fixed frequency offset. These population gratings store phase modulated identical data streams which incorporate a differential phase shift between them (e.g. 180 degrees). This pair of population gratings will generate two photon echoes separated in optical frequency by the fixed frequency offset. If these two photon echoes are collinear, and are allowed to beat on the detector, then a difference signal at the fixed frequency offset will be generated. This difference signal (at a convenient RF frequency) will have the relative phases of the two photon echoes impressed upon it. Thus the phase modulation of the input data can be recovered directly from the echo, without the need for a highly phase coherent external local oscillator. In addition, this technique alleviates the need for a highly coherent laser during the writing process. Any phase variations of the writing laser beam are encoded in the two population gratings as a common mode signal, and are suppressed during the mixing process on the detector during readback. The optical configuration needed to generate the two data channels is not excessively complex.

We were able to partially demonstrate this technique. We stored a phase modulated pair of gratings and attempted to recall them and to observe the phase modulation of the beat signal. The frequency offset was 80 Mhz, and the phase modulation was a square wave at a rate of 1 Mhz. We could observe the phase shift of the 80 MHz beat note at the 1 MHz rate very clearly in the prompt echo, but were unable to detect it in the stimulated echoe pulses due to irritating technical problems with the detector, and a low signal to noise ratio. These problems could be overcome in a straightforward manner, but unfortunately the contract expired before we were able to do so. We believe that the concept is very sound, and see no reason that it cannot be implemented with an improved apparatus.

REAL-TIME OPTICAL CORRELATOR

In collaboration with Randy Babbitt, currently at the University of Washington (AFOSR contract #F49620-93-1-0513) we demonstrated a real time correlator which utilized both phase modulation of a data stream and the capability to process data streams longer than the upper state lifetime of the material. A detailed description of this work which will be presented at the International Hole-burning Conference at the University of Tokyo in August, 1994 is attached. This work is also being written up for publication in Optics Letters.

The basic idea of the correlator is that the target data sequence is stored in the ground state of the material by conventional time domain spectral hole-burning techniques. The data is encoded as phase modulations of the laser frequency, rather than amplitude modulation. The data stream to be analysed phase modulates the laser beam. This laser beam stimulates the ground state population grating created by the (stored) target and creates a coherent transient. This coherent transient creates a photon echo which is proportional to the correlation between the stored target sequence and the continuously evolving data sequence. The length of the data sequence is arbitrary and can exceed the upper state lifetime of the material (as we have demonstrated). We were able to correctly identify all 120 occurances of the 13 bit target pattern in the 3120 bit data sequence. A theoretical calculation of the correlator response to the data sequence matches the actual measured output in all details, even predicting the partial correlations.

The demonstration of the real time correlator has several significant aspects. It is the first storage and retreival of actual digital data with phase modulation of the optical carrier which has been accomplished in a time domain spectral hole-burning system. Second, it is a spectacular verification of the concept of a real time correlator with arbitrary data sequence length. The incredible agreement of the data with modeling results provides a strong motivation to extend and expand the work. This work also pointed out the relationship of the laser frequency stability (coherence time) to the parameters of the data stream, such as data rate and target pattern length. The demonstration could not have been carried out without the stabilized laser system previously described.

ACKNOWLEDGEMENTS

This work was performed by Michael Jefferson of the IBM Almaden Research Center and Dr. Miao Zhu, presently with Hewlett Packard Laboratories. Professor Randall Babbitt of the University of Washington was a participant in the real time correlator experiments, and contributed enormously to the entire body of work described in this report. His advice and skills were critical to our success. Roger Macfarlane of the IBM Almaden Research Center was very helpful on many occasions, and participated in several of the experiments performed under this contract. We would like to thank Professor Thomas Mossberg, of the University of Oregon at Eugene for many valuable discussions. We wish to thank Dr. John Hall at JILA for the loan of the iodine cell and also for his guidance and encouragement in matters related to the stabilized laser. Finally, without the encouragement andsupport of Dr. Alan Craig of AFOSR this work would not have been possible.

APPENDIX 1: FREQUENCY DOMAIN RESULTS

High Density Frequency Domain Data Storage using a Stabilized Dye Laser

Miao Zhu* and C. Michael Jefferson

IBM Almaden Research Center, K65/802, 650 Harry Road, San Jose, Ca 95120

Phone (408) 927-2141 FAX (408) 927-2100

ABSTRACT

An externally stabilized, iodine-locked dye laser has been used to store 216 bits at a spectral density of 120 kHz/bit in the frequency domain in $Eu^{3+}:Y_2SiO_5$.

High Density Frequency Domain Data Storage using a Stabilized Dye Laser

Miao Zhu* and C. Michael Jefferson
IBM Almaden Research Center, K65/802, 650 Harry Road, San Jose, CA, 95120-6099
Phone (408)927-2141 FAX:(408)927-2100

There has been a great deal of interest in the use of rare earth doped materials such as Eu^{3+}:Y_2SiO_5 for ultra-high density data storage using time domain techniques [1,2,3,4]. These materials can exhibit T_2 times as long as 800 μsec or more[3,5] with corresponding projected linewidths of only several hundred Hertz. Since the typical linewidth of lasers used to investigate these materials (e.g. dye lasers) is of the order of 1 to 5 MHz, detailed studies of phenomena which can exploit the long coherence time of the excited state are difficult. Studies of phase modulation, continuous correlation, population gratings, free induction decay and so forth are greatly impacted by the laser linewidth. In addition, the actual linewidth of single persistent spectral holes has never been directly measured in these materials.

This source of experimental artifacts and imprecision can be greatly reduced or eliminated by stabilizing the laser utilizing techniques which clean up the phase and frequency jitter of the laser with either intra-cavity or external phase/frequency modulators, or both. Many of these techniques have been pioneered by Hall and Hansch[6]. This paper describes the implementation of such a laser stabilization system, and presents results obtained using it to burn and measure single and multiple spectral holes in the ground state of Eu^{3+}:Y_2SiO_5.

Commercial dye laser systems suffer from both short term jitter (linewidth of a few MHz), and longer term drift, which can be hundreds of MHz per hour. Both of these effects can be removed from the laser beam, in principle, by measuring the phase/frequency errors with a highly precise optical frequency reference, such as a cavity, and servoing the phase/frequency of the light with electro-optic (EOM) and acousto-optic modulators (AOM) to remove the fluctuations. The long term drift can be removed by changing the laser cavity length with either piezo controlled mirrors and/or a galvo driven Brewster plate.

For this experiment we used a Newport Supercavity with a 6 GHz free spectral range and 500 kHz linewidth (FWHM) as a short term optical frequency reference. The cavity length was stabilized actively by locking it to an iodine hyperfine transition. It is a great stroke of luck that there are fairly strong Iodine absorption lines within the absorption bands of both sites of the Europium ion doped into Y_2SiO_5.

The experimental apparatus is shown in Figure 1. The laser beam fast phase and frequency fluctuations are measured by observing the beat between a prompt reflection from the cavity entrance mirror and the cavity leakage field with detector D1. The laser beam is phase modulated with 40 MHz sidebands with EOM E2. The control system utilizes electro-optic modulator E1 and acousto-optic modulator A1, along with the laser tweeter and galvo plate to remove the phase and frequency fluctuations from the beam. A resultant laser linewidth of approximately 1 kHz relative to the cavity was produced, as estimated from loop error signals and measured cavity linewidths. This laser linewidth was degraded relative to the sample by structural vibrations, length drift, and (apparently) a microscopic domain noise in the PZT from which the Supercavity is constructed.

In order to reduce these effects, the length of the Supercavity was stabilized by a second servo loop which measured the laser frequency relative to an Iodine hyperfine transition using a saturation spectrometer. Acousto-optic modulators A2 and A3 allow frequency offsets (and subsequent fine tuning) of the laser frequency. The laser be[illegible] in the spectrometer is divided into a saturation beam, propagating CCW in the drawing, and a pr[illegible] beam, propagating CW. AOM A4 frequency shifts the saturation beam by 80 MHz, and chops it at 100 kHz, for subsequent lock-in detection. The saturation beam enters a White cell with approximately a 7.5 meter path in the Iodine cell. The probe beam is phase modulated at about 500 kHz and adjusted to be coaxial with the saturation beam. The deviation of the laser beam frequency from that of the hyperfine line is observed by a double lock-in technique using the signal from detector D3, and used to control the length of the Supercavity. A servo bandwidth of several kHz was achieved in this loop, limited by structural resonances in the Supercavity.

The stabilized and linewidth-narrowed laser beam passes through a set of computer controlled neutral density filters, and a pair of AOMs, A5 and A6, which allow precise offsets of the laser frequency relative to the Iodine line with a frequency synthesizer. The beam then enters the cryostat, passes through the sample, and is detected with a photomultiplier tube, D4.

Figure 2 presents the profile of a spectral hole burned with no frequency offset and subsequently scanned point by point by offsetting the laser frequency with AOMs A5 and A6. The laser was scanned over 200 discrete frequencies at a rate of 100 points per second. The sample of 0.2% doped $Eu^{3+}:Y_2SiO_5$ was maintained at 2K. The laser was locked to an iodine hyperfine transition at 580.054 nm, near the center of the Europium absorption band. The beam diameter was 4 mm, the sample was approximately 1 absorption length (3.6 mm) long, and the burning power density was 0.016 W/cm^2, corresponding to a beam power of 2 mW. The burning time was 20 msec. During scanning, the laser power was reduced to 20 nW. The line shape of the persistent spectral hole was Gaussian. The nonlinear-least-square fitting of the data gave an apparent linewidth of 48 kHz (FWHM). The dominant contribution of this linewidth was the random frequency noise (with low Fourier frequency and large RMS frequency deviation[7]) introduced by the reference cavity. The reduction of this frequency noise by the Iodine stabilization servo was limited by the signal to noise ratio of the Iodine transition within the required bandwidth. Ignoring the contribution of the linewidth of the material[3,5], the deconvolved linewidth of the persistent spectral hole was 34 kHz (FWHM), which was the actual laser linewidth. A better reference cavity with proper isolation would improve the actual laser linewidth dramatically[8]. Drift of the center of the fitted hole from the burning frequency was 200 Hz over a 10 second period.

Figure 3 shows a pattern of spectral holes representing the 216 bit ASCII representation of the phrase "IBM Almaden Research Center". A spectral hole represents a "1". The hole pattern was burned with the same parameters as above, but with a spacing of 120 kHz between bits in the frequency domain. This is a spectral density of 8333 bits/GHz, which to our knowledge is the largest spectral density yet achieved for frequency domain data storage, corresponding to about 50,000 bits per spot, if both absorption bands were utilized. Since the iodine transition was used as an absolute frequency reference, we were able to tune the laser frequency far away from this pattern of spectral holes, and tune it back to retreive the data.

In summary, a method of stabilizing a dye laser for precision measurements of hole-burning phenomena has been presented. The use of Iodine absorption lines to uniquely determine the absolute optical frequency of data stored in the material has been demonstrated. The use of such stabilized lasers will allow detailed studies of both the physics of the materials and also of techniques such as phase modulation which will allow eventual realization of data storage and processing applications.

This work was performed under Air Force Office of Scientific Research Contract #F49620-92-C0066. We would like to thank Dr. John L. Hall for helpful discussions and the loan of the Iodine cell.

* Current address: Hewlett-Packard Laboratories, 26M, P.O.Box 10350, 3500 Deer Creek Road, Palo Alto, CA 94303-0867.

References

1. T.W.Mossberg, Optics Lett. 7 (1982) 77.
2. W.R. Babbitt and T.W. Mossberg, Optics Communications 65 (1988) 185.
3. R.Yano, M.Mitsunaga, and N. Uesugi, J.Opt. Soc. Am B 9 (1992), 992.
4. Y.S.Bai and R. Kachru, Optics Lett. 18 (1993), 1189.
5. R.W.Equall,Y.Sun, R.L.Cone, R.M. Macfarlane, Phys.Rev.Lett, to be published.
6. J.L.Hall and T.W. Hansch, Optics Lett. 9 (1984) 502.
7. M.Zhu and J.L.Hall, J.Opt.Soc.AM. B10, 802 (1993).
8. M.Zhu and J.L.Hall, 1992 IEEE Frequency Control Symposium, Hershey, Pa.,1992.

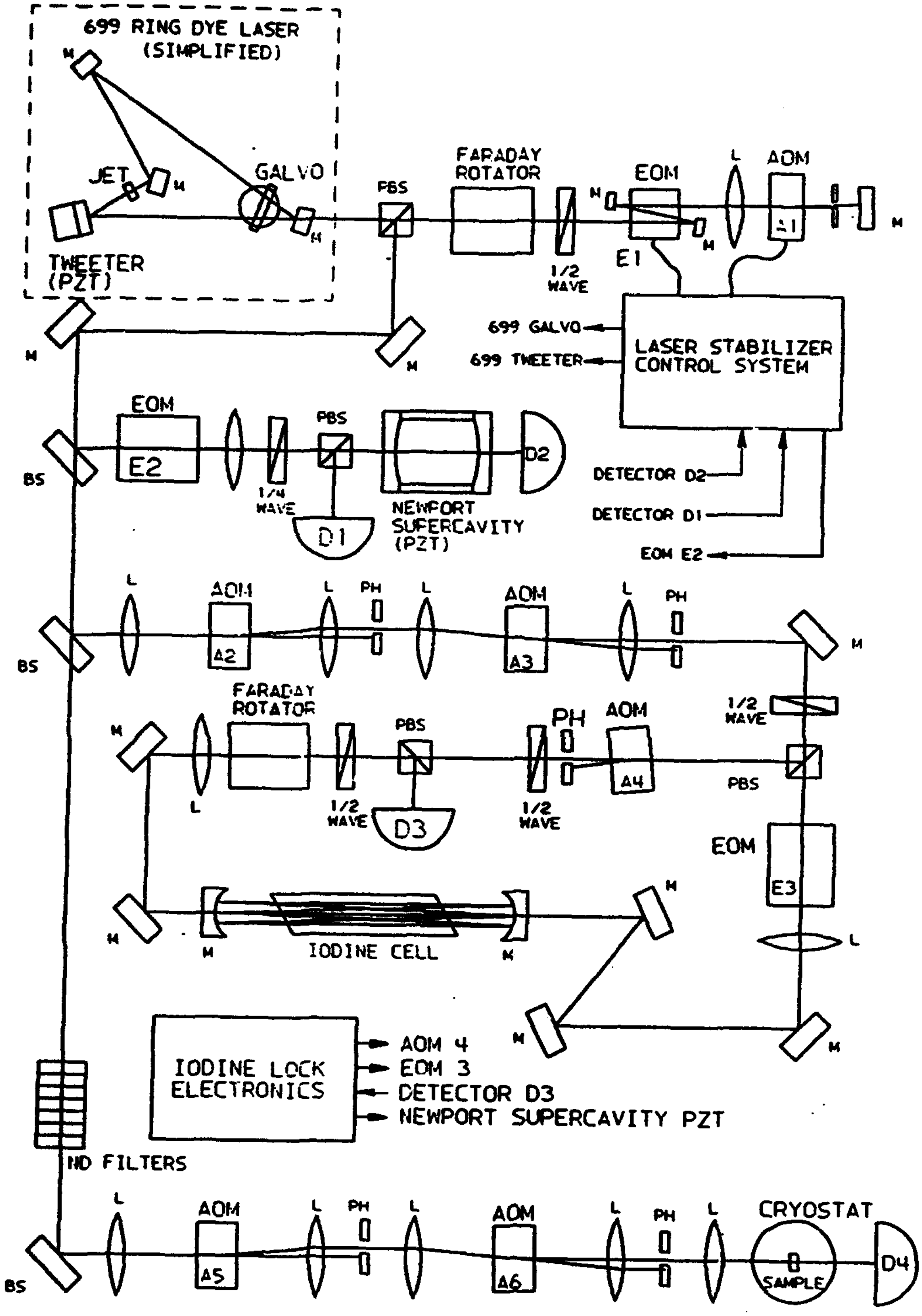

Figure 1: Iodine-Locked, Frequency Stabilized Dye Laser Apparatus.

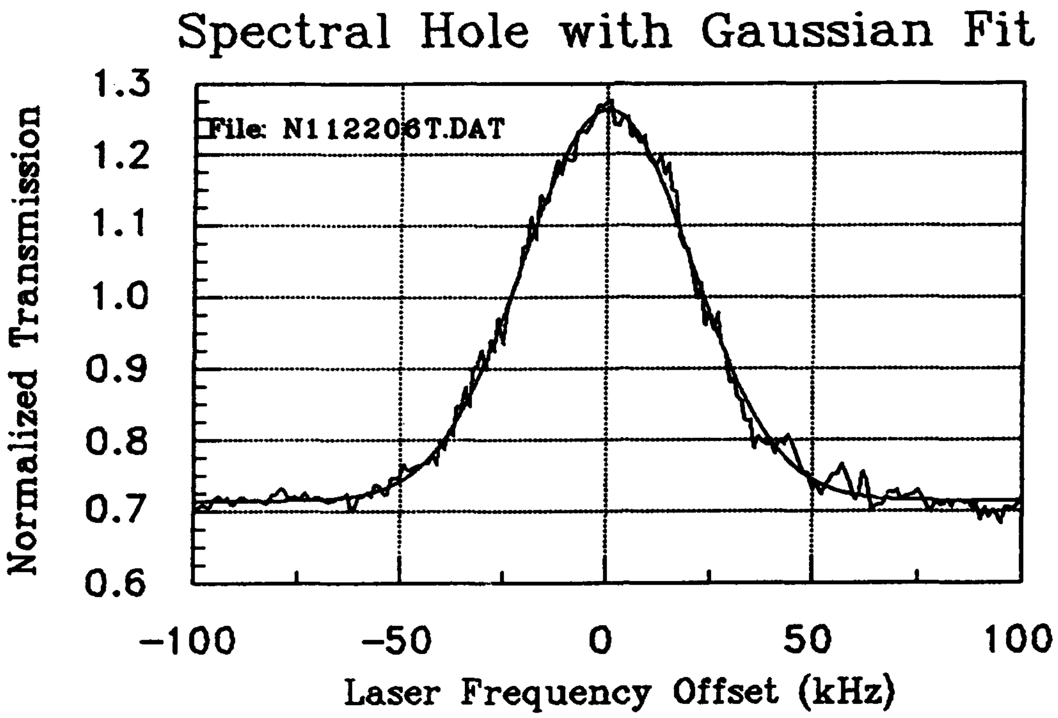

Figure 2: Single Spectral Hole with fit to a Gaussian.

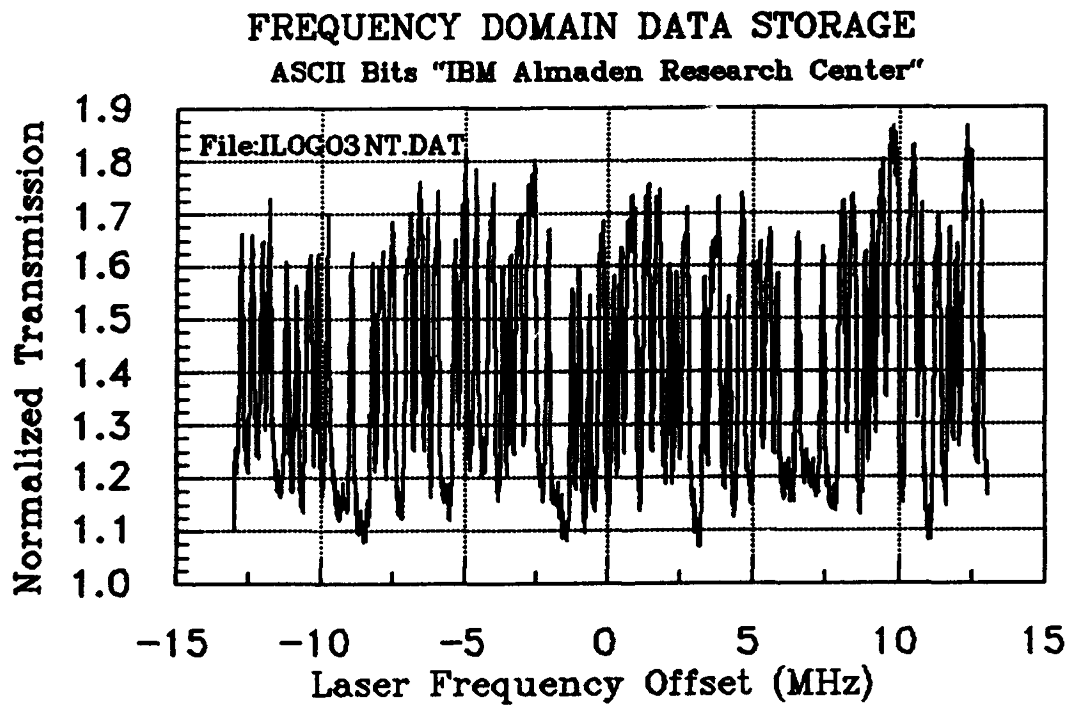

Figure 3. 216 Bit Spectral Hole Data Storage at 120 kHz/bit.

APPENDIX 2: REAL TIME CORRELATOR RESULTS

Coherent Transient Continuous Optical Processing in a Solid

Miao Zhu and C. Michael Jefferson

IBM Almaden Research Center, K65/802, 650 Harry Road, San Jose, CA 95120

Phone (408) 927-2141 FAX: (408) 927-2100

and

Wm. Randall Babbitt

University of Washington, Dept. of Electrical Engineering, FT-10, Seattle, WA 98195

Phone: (206) 543-2168 FAX: (206) 543-3842

ABSTRACT

A 3120-bit data stream of duration exceeding the absorbing transition's upper state lifetime was correlated with a 13-bit pattern in $Eu^{3+}:Y_2SiO_5$ using coherent transient techniques.

Coherent Transient Continuous Optical Processing in a Solid

Miao Zhu† and C. Michael Jefferson
IBM Almaden Research Center, K65/802, 650 Harry Road, San Jose, CA 95120
Phone (408) 927-2141 FAX: (408) 927-2100
and
Wm. Randall Babbitt
University of Washington, Dept. of Electrical Engineering, FT-10, Seattle, WA 98195
Phone: (206) 543-2168 FAX: (206) 543-3842

When a sequence of temporally modulated optical waveforms illuminate an inhomogeneously broadened absorbing medium, the resultant optical coherent transient output signal's represents the cross-correlation or convolution of the input temporal waveforms.[1] The projected performance characteristics of coherent transient processors include data rates greater than 10 GHz, time-bandwidth products far in excess of 10,000, and the ability to fully process both amplitude and phase modulated waveforms.[1,2] Previously it was assumed that the input data stream and pattern stream must both be shorter than the absorbing transition's homogeneous dephasing time and must both be reentered in order to process longer or multiple data streams.[1] It has recently been proposed that patterns could be permanently stored in an inhomogeneously broadened solid and that input data streams of indefinite length could be continuously processed in real time without the need to reenter the input pattern.[3,4] In this paper, we present a proof of concept demonstration of an optical coherent transient continuous correlator.

The programming and processing steps for the continuous optical processor require an inhomogeneously broadened absorbing medium in which excited absorbers either decay or are gated into a metastable ground state that is not resonance with wavelengths of the optical waveforms to be processed. To program this medium, two temporally modulated optical waveforms illuminate the medium, temporally separated and angled with respect to each other. For an optical correlator, the two input waveforms are a pattern stream followed by a brief reference pulse. Provided these waveforms are within the data bandwidth of the medium (roughly the inhomogeneous bandwidth of the absorbing transition) and shorter than the transition's homogenous lifetime, the medium will respond to the combined power spectrum of the two waveforms. The combined power spectrum contains an interference term proportional to the product of the Fourier transforms of the waveforms, which is stored in the spectral population distribution of ground state absorbers in the medium. This spectral holographic grating produced by temporally separated waveforms is analogous to the spatial hologram produced from the interference of two spatially modulated light beams with angular separation.

The resultant population grating acts as a spectral filter on the Fourier components of subsequent optical data streams yielding an output signal which is the cross-correlated of the data streams with pattern stream. The data stream is not limited by the homogeneous decay time, but may continue to be processed for as long as the spectral population grating persists. Three phenomena act to limit the grating lifetime: 1) saturation of the transition by the data stream, 2) the decay of the metastable state absorbers back to their original ground states, and 3) optical pumping of the ground state grating to the metastable state. The saturation effect can be minimized by sufficiently lowering the input optical intensity of the data stream. The decay of the metastable state depends on the material used, but can stored data has been shown to last well

over a day in some materials. A gating step could be added after the second optical waveform to "fix" the ground state population distribution (for example, photoionization of the absorbers that are in their excited state after the second waveform). Following the gating step, an absorber subsequently excited by the data stream would decay back to its ground state distribution and restore the programmed spectral grating. Other the limiting factors mentioned above, there is no limit on the processed data stream's duration.

A material that embodies all the required parameters to demonstrate the continuous coherent transient correlator's full potential has yet to be found. In this proof of concept demonstration storage was accomplished using population storage in the ground state hyperfine levels of the 579.9 nm $^7F_0$-$^5D_0$ transition in Eu^{3+}:Y_2SiO_5. Population gratings in these levels can persist well over an hour.[5] One drawback to hyperfine storage is that it is a single photon storage process and thus during processing cycle the partially erases the programmed grating (the third limiting effect mentioned above). By lowering the data stream intensity, this effect was minimized so that data streams longer than the upper state lifetime could be processed.

Figure 1 illustrates the timing of the input waveforms used in our experiment. The pattern stream and the data stream were collinear and angled 4.6° with respect to the brief reference pulse. Their optical waveforms were generated by acousto-optically modulating the cw output of a commercial ring dye laser which was locked to an external cavity. Precise control of the waveform's phase and amplitude was accomplished using an 800 MHz arbitrary waveform generator as the rf source for the acousto-optic modulators. The pattern stream lasted 13 μsec and was binary phase modulated at a 1 MHz data rate with a 13-bit Barker code (1,1,1,1,1,0,0,1,1,0,1,0,1). The brief reference pulse arrived 3 μsec after the end of the pattern stream, was 1 μsec in duration, and had a pulse area of roughly $\pi/2$. The pattern stream's intensity was roughly 1/40 of the brief pulse's intensity. After a delay of 6.24 msec, the data stream started and lasted 3.12 msec. The data stream was binary phase modulated at a 1 MHz data rate and was made up of fifteen 16-segment long sequences. Each 13-bit long segments either matched the pattern 13-bit Barker code ("P") or were noise segments. Two different noise segments were used: the first ("N1") was (1,0,1,0,1,1,0,0,0,1,1,1,1) and the second ("N2") was (1,0,0,1,0,0,0,1,1,1,1,1,1). The 16-segment long sequence was made up of a combination of these 13-bit long segments: (P,P,N1,N2,P,N1,P,P,N1,N2,N1,P,N1,P,N2,P). This sequence was repeated 15 times to yield the data stream. Thus, the entire data stream was 13x16x15 = 3120 bits long. The intensity of the data stream was 1/74 the pattern stream's intensity.

The 0.2% Eu^{3+}:Y_2SiO_5 sample was cooled to 1.9 K and had a small signal absorption of 65%. The measured homogeneous dephasing time (T_2) was 600 μsec. The output signal was concurrent with the data stream, but spatially separated due to the angular separation of the input waveforms. A gating acousto-optic modulator was used to block the intense brief pulse from entering the photomultiplier tube used for detection. An annealing process was used before the experiment to erase any previous population gratings. The recorded trace in figure 2 was the result of a single storage and single processing event. The programmed gratings were *not* accumulated and the output signal is *not* the average of multiple traces.

Figure 2 shows the 3.12 msec output signal broken into five contiguous 0.624 msec plots (the five lower plots). To emphasize, the five plots represent a single recorded output signal generated by a single 3120-bit long data stream. The trace was broken up only for presentation purposes. All five plots are scale identically. In both figures, the minor tick marks correspond to the 13-bit long pattern or noise segments and the major tick marks correspond to the 16-segment long

sequences. The top trace in figure 2 is the calculated correlation of the pattern stream and the data stream. The output signal matched the calculation very well. The 120 large peaks in the output signal correspond to the 120 appearances of the pattern segment in the data stream. Even the smaller, partial correlations during and between the noise segments were faithfully detected. The duration of the data stream was limited by the data acquisition system and was chosen to be longer than the 2.0 msec upper state lifetime[5] to illustrate the "continuous" nature of the processing. The output signal does not show any significant decay in size or fidelity during this 3.12 msec long time interval. In a two-level system without population storage, the decay of the upper state would lead to a factor of 23 reduction in the output signal's amplitude from beginning to end. The observed slight reduction in size from beginning to end may come from a reduction in the grating due to the above mentioned optical pumping of the hyperfine levels by the data stream.

To correctly process the data stream, the optical carrier frequency drift between the pattern and data streams must be less than one over twice the duration of the pattern stream (less than 38 kHz for the pattern stream used). The small fluctuations in the peak heights may have been due in part to fluctuations in the external reference cavity resonant frequency. Increased laser frequency fluctuations were observed to lead to a considerable drop in the output signal's fidelity.

The results presented show that continuous processing of optical waveforms using optical coherent transients is possible. The 3120-bit long data stream was not limited by the absorber's homogeneous dephasing time (T_2) nor the upper state population lifetime (T_1) of the absorbing transition. The performance of one implementation of a coherent transient processor with a gateable material has been evaluated and the expected data bandwidth, time-bandwidth product, and pattern storage density are 5 GHz, 16,000, and 110,000 patterns per square centimeter, respectfully.[4] This is a continuous real time, phase sensitive optical correlator with a propagation delay less than the absorber's homogeneous decay time(on the order of microseconds) and no dead time. The high pattern storage density allows multiple patterns to be stored, fixed, and accessed randomly on microsecond time scales by spatial addressing techniques (i.e. acousto-optic or electro-optic deflectors). Such a coherent transient continuous optical processor would be well suited for pattern/target recognition or encoding/decoding applications.

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†Current Address: Hewlett-Packard Laboratories, 26M, P.O. Box 10350, 3500 Deer Creek Road, Palo Alto, CA 94303

1) Y. S. Bai, W. R. Babbitt, N. W. Carlson, and T. W. Mossberg, Real-time optical waveform convolver/cross correlator, Appl. Phys. Lett. 45, 714 (1984).

2) J. A. Bell and W. R. Babbitt, "Phase and frequency sensitive signal processing using stimulated photon echoes", Conference on Lasers and Electro-Optics, 1990 Technical Digest Series, Vol. 7, (Optical Society of America, Washington, DC 1990), pp 420-421. Anaheim, CA, May 21-25, 1990.

3) W.R. Babbitt and J. A. Bell, Continuous signal processing using optical coherent transients, Spectral Hole-Burning and Luminescence Line Narrowing: Science and Applications Technical Digest, 1992 (Optical Society of America, Washington, D. C., 1992) Vol. 22, pp. 222-225.

4) W. R. Babbitt and J. A. Bell, Coherent transient continuous optical processor, to appear in Applied Optics, Volume 32, Number 8, March 10, 1994.

5) M. Mitsunaga, "Time-domain optical data storage using Eu^{3+} ions in crystals", in Technical Digest on Persistent Spectral Hole-Burning: Science and Applications, 1991 (Optical Society of America, Washington, D. C., 1991) Vol. 16, pp. 170-172.

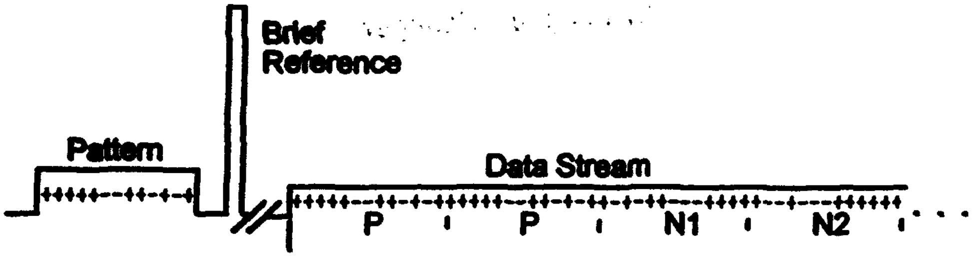

Figure 1 The timing of the input optical waveforms (not to scale). The +'s and -'s indicate the binary phase encoding of the pattern and data stream. The two backslashes in the input sequence indicate a long delay between the brief reference waveforms and the start of the data stream. The three dots indicate that the data stream continues.

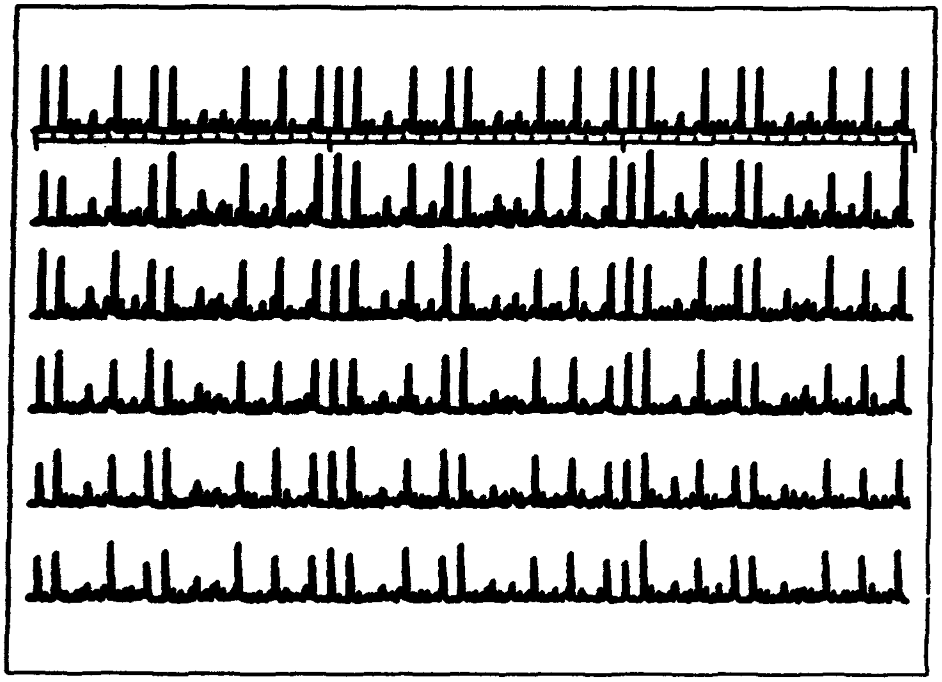

Figure 2 The calculated output signal (upper plot) and the experimental output signal (lower trace, broken into five contiguous plots). Of the lower five traces, the top is the first 624 μsec of the trace of the output signal, the second from the top is the second 624 μsec of the trace, and so on. The output signal shown is one 3.12 msec long, single event trace. The vertical alignment of the peaks is due to the 15 repetitions of the pattern/noise sequences. The horizontal and vertical scales are identical for all five plots. The minor and major tick marks are separated by 13 μsec 208 μsec, respectively. The digitization rate was 2 MHz.